Validation of New Generation Tooling Concept for Electroplating of Copper on Printed Circuit Boards

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A dynamically software-controlled electroplating tooling concept has been developed to compensate the pattern dependence of the deposited layer thickness on different substrates. In this paper a validation of this new tooling concept on industry relevant printed circuit boards is presented. Simulations are compared with experimental results as obtained in a prototype electroplating cell. A quantitative improvement of the plating thickness uniformity between a standard electroplating cell and the advanced tooling approach is given. The influence of the conductivity of the electrolyte on the deposit distribution is studied and indicates a way to obtain a significant improvement in uniformity.

Keywords: *Printed circuit boards, pattern plating, acid copper plating, computer simulation*

Introduction

A dynamically software-controlled electroplating tooling concept** has been developed where the pattern dependence of the deposited layer thickness on substrates (*e.g.*, printed circuit boards or semiconductor wafers) can be significantly reduced. The main change from a standard cell is the introduction of a controllable grid of anode segments, at a small distance of the substrate as shown in Fig. 1 on the right. In the implementation as presented here, the anode segments consist of rods covered with an inert anode material like platinum or IrOx depending on the application.

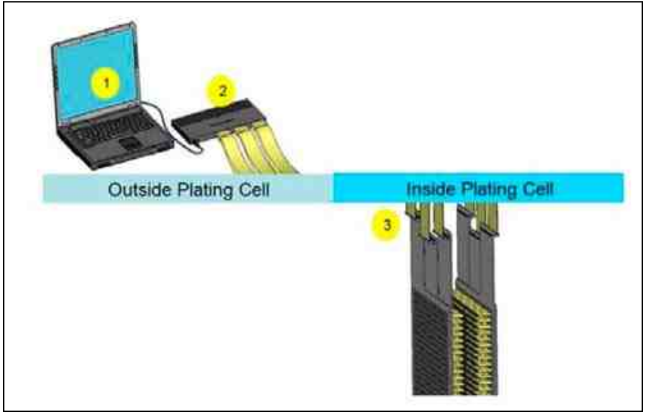

Figure 1 - Implementation of the new tooling concept.

As indicated in Fig. 1, the proposed solution consists of:

1. A simulation tool that optimizes the current on each anode segment in time to yield the desired (*e.g.*, uniform) deposition over the patterned substrate. These simulations take all relevant effects like cell design, pattern on the substrate and resistivity of the substrate into account. The results of the optimization are sent to the control unit and feeding network.

2. The feeding network contains a microprocessor that reads the calculated pattern of current, and then controls an array of DACs, which imposes the correct current on each anode segment. If needed, an amplification of the current can be implemented.

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3. A holder (*e.g.*, printed circuit board with multiple layers, depending on the current and the number of anode segments) on which the anode rods are mounted, and which connects each rod individually to the feeding network through a series of connectors.

As the current on each of the anode segments can be individually controlled and changed in time, any desired pattern can be imposed. This means that based on simulations, the current on each of the anode segments can be determined upfront to yield a very uniform deposition, almost regardless of the pattern and/or resistivity of the substrate. As the current on each anode segment can also be varied over time, the plating process can be designed to take the change in resistivity of the conducting layer on the substrate as more metal is deposited into account. The optimization software can also take the effect of movement of the substrate into account and adapt the current pattern in time accordingly.

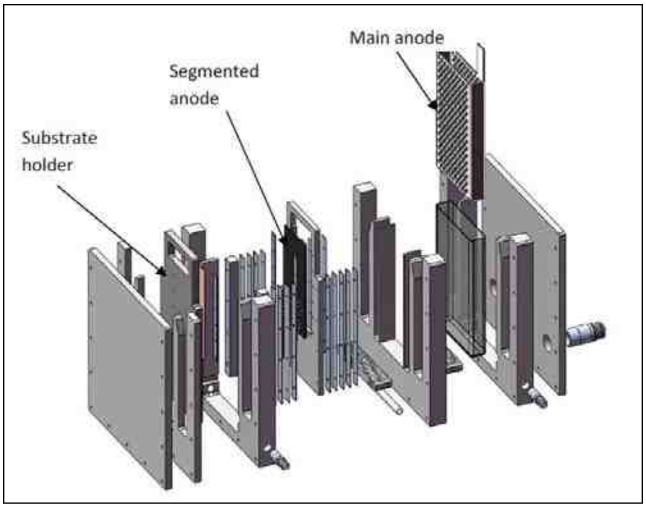

Figure 2 - Schematic view of the test cell.

Lab scale validation

Set-up

A schematic view of the prototype cell used for the experiments is shown in Fig. 2. The segmented anode is positioned in the middle of the cell, the cathode substrate on the left hand side. The distance between the tip of the anode pens and the substrate can be adapted by adding or removing one or more one-millimeter thick PVC spacers.

A lab set-up as shown in Fig. 3 was constructed to validate the new tooling concept. The segmented anode consisting of 8 × 8 segments, as shown in Fig. 4, is inserted into the plating cell opposite the substrate. The current on each of the anode rods can be controlled individually. Each anode is 3 mm in diameter and the distance between two anode segments is 14 mm.

A proprietary acid copper electrolyte*** is used in these tests, one that is widely used in the semiconductor industry. It needs to be noted that this electrolyte has been tuned to yield uniform distributions even when the anode or cathode is not uniform or patterned. This of course means that a significant part of the advantage of the segmented anode is counteracted by the electrolyte.

Additionally different "simple" electrolytes with different conductivities were tested to study the influence of the conductivity and throwing power on the performance of the segmented anode. The basic electrolyte is copper sulfate with polyethylene glycol (PEG) and Cl^-, with different amounts of sulfuric acid to change the conductivity from 25 up to 50 S/m.

Polarization measurements were performed on the different electrolytes in order to obtain all the necessary input data for the simulations. Experiments at different rotation speeds (100, 400 and 800 RPM) were performed in order to assess the influence of the mass transport on the plating behavior.

Figure 3 - Lab scale set-up.

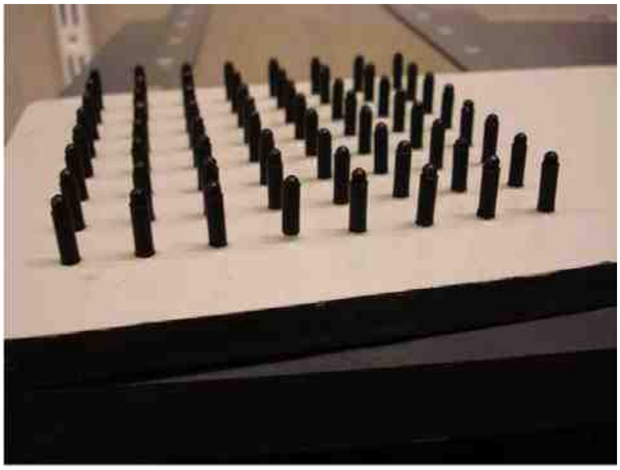

Figure 4 - Segmented anode with platinum-coated rods.

**** Rohm&Haas Coppergleam 125 T-2 A, Rohm & Haas, Subsidiary of the Dow Chemical Co., Midland, MI, USA.*

The polarization curve for the proprietary electrolyte, corrected for the ohmic drop, obtained for 800 RPM is shown in Fig. 5. The corresponding electrolyte conductivity is 53.3 S/m. As no sample of anode material in a usable size for the rotating disk electrode was available, it was not possible to perform the polarization measurements for the anodic part of the curve. As the main reaction on the anode is the production of O_2 for which the reaction rate is almost independent of the overpotential, a linear, quasi-primary distribution is assumed. It is not expected that this has any influence on the accuracy of the simulations and optimizations.

In collaboration with ACB (Dendermonde, Belgium, www.acb.be), custom small printed circuit boards were designed and produced to ensure a maximum relevance of the lab scale tests. These printed circuit boards each contained an 8 × 8 cm portion of an industrial printed circuit board design. A typical example is shown in Fig. 6. The 8 × 8 patterns are positioned on panels that fit exactly in the prototype plating cell opposite the segmented anodes, allowing an exact control of the position of the segmented anodes relative to the pattern. Figure 7 shows one of these panels mounted in the cathode holder. The copper strip at the top the panel is used to connect the panel with the multi-channel current source outside the electrolyte. During the testing, two different patterns on the panels were used to verify that the improvement was not limited to a specific pattern design. They are labeled Pattern 1 and Pattern 2 in the subsequent sections.

Using the optimization algorithm, the optimal current on each anode segment was calculated. The resulting deposit distribution and the position of each of the 8 × 8 anode pens relative to the pattern are shown in Fig. 8. The layout corresponds exactly to the configuration of the anode pens relative to the PCB as mounted in the prototype cell. It is evident that the resolution of the pattern is much finer than the resolution of the anode segments. It is not realistic to increase the number of anodes beyond a certain point. The minimum geometric distance at which a separate anode is still active is determined by the relative magnitude of the ohmic drop in the electrolyte and the resistance of the deposition reactions.

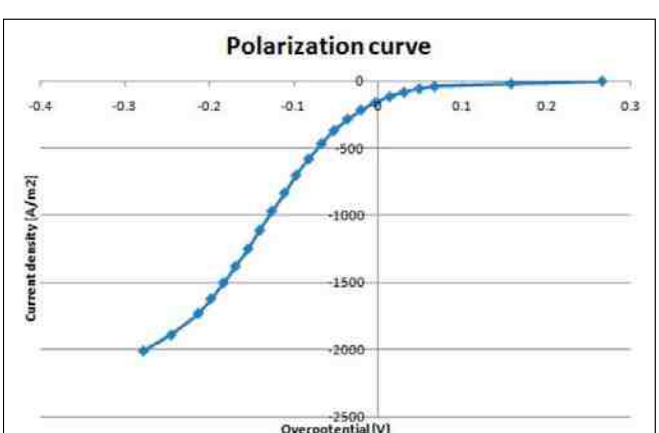

Figure 5 - Measured polarization curve of the proprietary copper electrolyte at 800 RPM.

From calculations the minimum distance for the copper electrolyte is about 5 mm. It does not make sense to position the anode sections closer than 5 mm apart as the polarization will then be the dominant factor governing the local current density and deposit distribution. This then means that the segmented anode has lost all its compensating power. The polarization can only be changed by changing the chemistry (concentrations of the different species, additives, etc.) as is clearly demonstrated by the change in electrolyte as reported in the next sections of this paper.

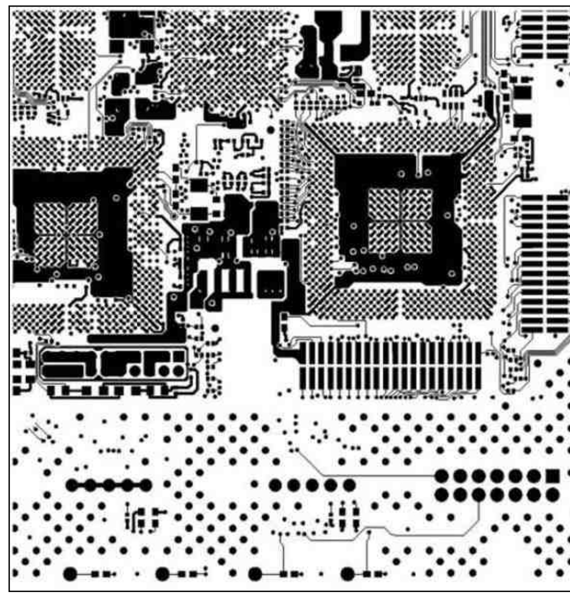

Figure 6 - Typical example of a small printed circuit board.

Figure 7 - Panel with Pattern 1 mounted in the cathode holder.

The deposited copper thickness was measured by x-ray fluorescence (XRF) at 20 reference points of the pattern. A suitable calibration of the XRF, based on standard copper foils was performed to ensure maximum accuracy. Before deposition, the copper seed layer thickness was measured to be able to calculate the actual deposited value accurately. The reference points were selected to ensure that the x-ray beam was no wider than the structures to be measured to avoid errors in the measurements.

In order to assess the benefits of the new tooling approach, experiments with the main anode alone and with the segmented anode alone were performed. The measured deposit thickness was compared with simulations for both cases.

Figure 9 shows a comparison between the simulated and measured deposit thickness for Pattern 1, using the main anode configuration. An excellent agreement between the simulations and the experimental values is observed, again showing the validity of simulations in optimization the plating thickness distribution.

Figure 10 compares the measured deposit in the 20 predefined sample points for the two configurations of Pattern 2. The variation of the deposit thickness is clearly reduced by the segmented anode. The standard variation is reduced from 36% for the main anode configuration to 23% for the segmented anode configuration. Note that both the lowest and the highest deposition values are improved. If another target value for the optimization is selected, it is possible to focus the improvement more towards increasing the lowest values or decreasing the highest values. This choice depends on the requirements of the customer and is not investigated further here. From these measurements, the improvement of the deposition uniformity is evident. Different experiments on different patterns show a very similar behavior. Within the range examined in the experiments, no significant influence of the distance between the segmented anode and the substrate was detected. This is mainly due to the very high conductivity of the commercial copper plating electrolyte which ensures that the ohmic drop in the electrolyte is not the determining factor in the distribution of the current density on the patterned substrate.

Experiments performed with an in-house standard copper plating electrolyte consisting of copper sulfate and sulfuric acid show the influence of the electrolyte conductivity on the deposition distribution. A limited amount of PEG + Cl^- was added to ensure the adhesion and improve the quality of the electrodeposited copper layer. The conductivity of this electrolyte was 25 S/m, half of the value of the commercial electrolyte. From the experiments, as shown in Fig. 11, it is clear that the reduced conductivity of the electrolyte yields a significant improvement in deposition uniformity. The standard deviation is reduced from above 17% for the commercial electrolyte to below 11%. This means that for this electrolyte, the copper thickness at all measured points is within 20% of the average value. Note also the very significant improvement when comparing the distribution

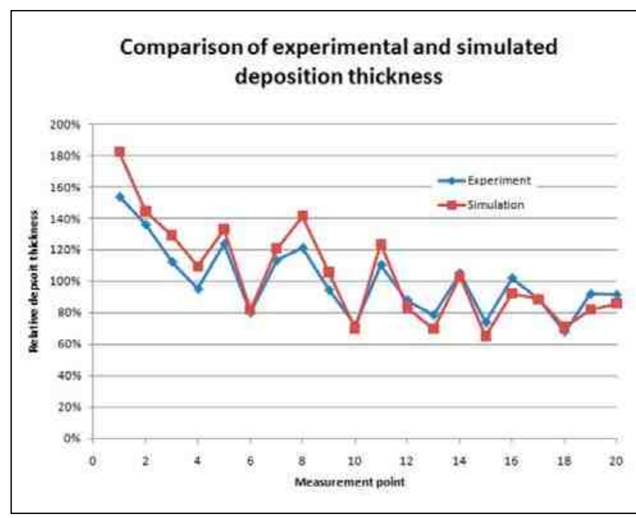

Figure 9 - Comparison of experimental and simulated deposition thickness for Pattern 1.

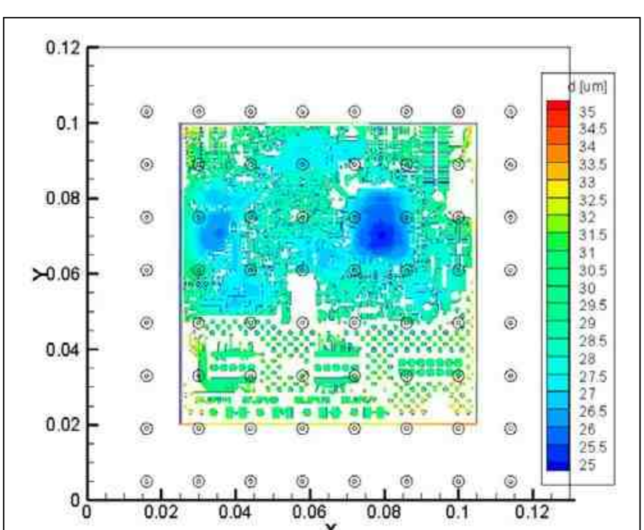

Figure 8 - Calculated copper thickness distribution over Pattern 1.

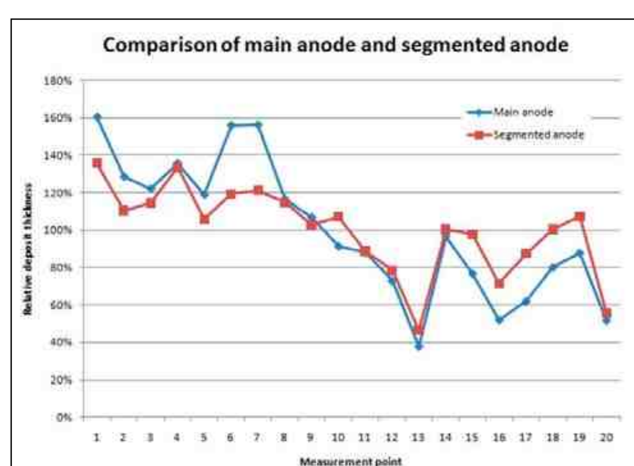

Figure 10 - Comparison of main anode and segmented anode for Pattern 2.

using the segmented anode and the optimized electrolyte (Fig. 11) with the distribution from only the main anode and the standard electrolyte (Fig. 9). Based on these results, it can be concluded that it would be very beneficial to tune the electrolyte and the segmented anode approach together to achieve maximum uniformity in the plating distribution.

Additional experiments using the Pattern 2 design show that the improvement of the uniformity achievable with new tooling depends strongly on the electrolyte conductivity. Table 1 shows the standard deviation as measured over the 20 sample points for the two electrolytes, each time with the main anode and with the segmented anodes. It is clear that the best results are achieved with a less conductive electrolyte combined with the segmented anodes.

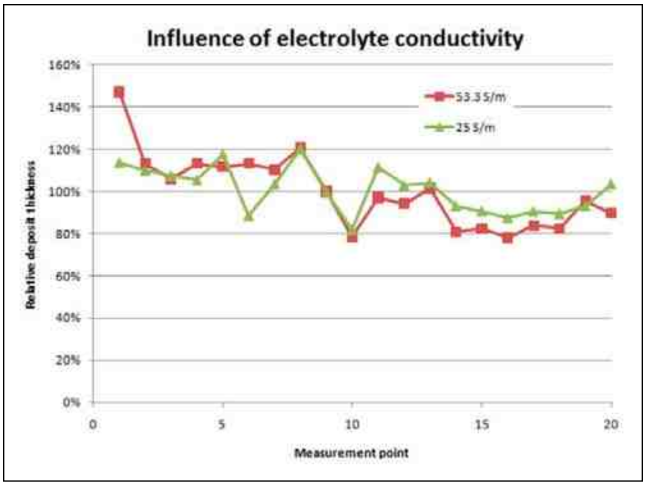

Figure 11 - Influence of the conductivity of the electrolyte on the deposition distribution on Pattern 1 using the segmented anode.

Table 1

Standard deviation of the distribution for the different configurations

	Electrolyte 53.3 S/m	Electrolyte 25 S/m
Main anode	22.4 %	39 %
Segmented anode	17.1 %	11 %

Conclusions

From the results as presented above it can be concluded that the validity of the new tooling approach has been clearly demonstrated for industrially relevant printed circuit boards. The gain in uniformity of the deposition as achieved in the experiments is significant.

The proposed tooling concept yields a significant increase in the overall control of the deposit distribution. The electroplating cell actively compensates the non-uniformity in the deposit based on upfront simulations and optimization.

Different targets and specification for the optimizations are possible depending on the user requirements:

- More uniformity with the same current density
- Higher plating speed/throughput with same uniformity
- Increasing the minimum deposit or decreasing the maximum deposit with limited influence on the rest of the distribution
- Combinations of the above

It was established that the control of the deposit distribution can be further improved when the electrolyte is tuned together with the hardware.

The resulting increase in plating control is important to a production plant for PCBs for several reasons:

- It allows plating at higher speed, thus improving throughput.
- It reduces the consumption of copper.
- It relaxes the design rules (*e.g.*, the width and distance between single tracks, isolated vias, etc.), so more complex designs can be produced reliably.

Acknowledgements

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About the authors

Gert Nelissen *graduated from the Vrije Universiteit Brussel (VUB, Belgium) (1993) with a M.Sc. degree in Electromechanical Engineering. From 1993 to 2003, he worked at the Electrotechnics Department (ETEC) of the Vrije Universiteit Brussel where he received a Ph.D. in electrical engineering (2003). His thesis title was "Simulation of Multi-ion Transport in Turbulent Flow." His main research interests include the modeling of turbulent flow and mass transfer and the simulation of complex electrochemical system including various deposition processes and anodizing. As co-founder of Elsyca, Dr. Nelissen acted as consulting and engineering manager, mainly focusing on projects including flow and mass transfer until the end of 2007. Since then, he has been responsible for research and technology development within Elsyca, comprising all externally funded and strategic research projects.*

Dr. Alan Rose *is an elected fellow of the Institute of Mechanical Engineers in the U.K., with a B.Sc. in Aeronautical Engineering and a Ph.D. in Chemical and Process Engineering. He currently holds Research Fellow positions at Manchester University and Liverpool University, where he has been involved in flow-related research and training of graduates and postgraduates in computational fluid dynamics. Dr. Rose is a long-time advocate of engineering simulation tools and has been involved in verification, validation, implementation* *and simulation programs with the U.S. Air Force, Rolls-Royce, DuPont and Johnson Matthey, to mention a few. For the past five years, he has been instrumental in the adoption and application of software simulation tools in electrochemical process industries, such as plating, machining and even corrosion. Dr. Rose is currently based in Atlanta and is responsible for Elsyca's North American business.*

Paulo Vieira *graduated from the Universidade de Coimbra (Portugal) with a licentiate degree in Industrial Chemistry in 2005. Paulo then joined Electrofer IV, a leading automotive electroplating company in Portugal where he first held responsibilities in production. Paulo became responsible for Development in 2007, ensuring process optimization, testing and approval of prototype parts. In 2008, Paulo joined Elsyca´s engineering team where he currently works on consulting projects as a project engineer. Paulo has been active mainly in functional plating but also in decorative plating, electropolishing and electrocoating.*

Dr. Bart Van den Bossche *graduated from the Vrije Universiteit Brussel (VUB, Belgium) with a M.Sc. degree in Metallurgical Engineering in 1991. He received a Ph.D. in Electrochemical Engineering in 1998. Bart is Elsyca's Engineering Manager for Surface Finishing projects. Bart has been active in electrochemical process computer modeling for over 15 years, as reflected in a series of peer reviewed papers. In addition, Bart has a long track record as a consultant for electrochemical cell and tooling design in the plating, electroforming and electrochemical machining industry. As Elsyca co-founder, Bart is in charge of several Elsyca consulting projects.*

People in the News

Linetec's Tammy Schroeder earns LEED Green Associate certification

Tammy Schroeder, Linetec's senior marketing specialist, successfully passed the U.S. Green Building Council's (USGBC's) Leadership in Energy and Environmental Design® (LEED®) Green Associate Certification. LEED education, certification and accreditation are encouraged as part of the company's environmentally-responsible practices and support for customers' green design and building projects.

Schroeder adds her status as a LEED Green Associate to more than a decade of experience with Linetec (Wausau, WI), the nation's largest, independent, architectural finishing company. She has written dozens of articles to give architects, contractors and manufacturers insight into all of the eco-friendly, architectural finishing technologies - paint, powder coat and anodize.

In addition to authoring articles, Schroeder develops and maintains the company's American Institute of Architects/Continuing Education System (AIA/CES) programs. She also manages the company's award-winning website, Linetec.com, as well as its enewsletters and other educational resources.

Located in Wisconsin, Linetec serves customers across the country, finishing such products as aluminum windows, wall systems, doors, hardware and other architectural metal components, as well as automotive, marine and manufactured consumer goods. Part of Apogee Enterprises, Inc., Linetec provides leadership in green building through practical yet distinctive products and services to enclose green commercial buildings, delivered through sustainable business practices. Exemplifying these practices, Linetec has been a member of the USGBC since 2005. For more information about Linetec and its green initiatives, please visit http://www.linetec.com or e-mail sales@linetec.com.

ASTM International Committee on Metallic-Coated Iron and Steel Products honors Richard L. Nester with Award of Merit

Richard L. Nester, general manager of quality assurance and customer service at Wheeling-Nisshin Inc. in Follansbee, WV, has received the 2010 ASTM International (W. Conashohocken, PA) Award of Merit and accompanying title of fellow from ASTM Committee A05 on Metallic-Coated Iron and Steel Products. Nester received the Award of Merit, which is ASTM's highest organizational recognition for individual work on standards activities, for his significant contributions to Committee A05 and the development of product specifications and management of terminology for metallic-coated sheet.

A member of ASTM International since 1995, Nester is a member of the A05 executive subcommittee (A05.90) and has served as the long-time chair of Subcommittee A05.18 on Editorial and Terminology. He also works on Committees A01 on Steel, Stainless Steel and Related Alloys and B02 on Nonferrous Metals and Alloys. After earning a bachelor's degree in metallurgy from the Pennsylvania State University, University Park, PA, in 1974, Nester spent several years as a metallurgical engineer at Weirton Steel Corp., Weirton, WV. In 1987, he became Manager of the Quality Department at Wheeling-Nisshin Inc., and was promoted to his current position in 1995. Nester specializes in hot-dip metallic-coated steel sheet products. In addition to ASTM International, Nester is a member of the Association for Iron and Steel Technology and SAE International. He also served a four-year term on the Governing Board for the Galvanizers Association, and received the association's Chairman's Award in 1998. He holds a master's degree in business administration from the University of Steubenville, Steubenville, OH.